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STIFFNESS AND SLIP IN MULTI-DOWEL FLITCH-PLATE TIMBER CONNECTIONS

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ABSTRACT: Large multi-dowel connections can provide the strong and ductile connections required for large, highly-loaded timber structures, but their slip under load is not well understood. This is important because accumulated local displacements at connections can have significant implications for overall building serviceability. Empirical relationships for the slip of a single-dowel connection do not capture the dowel interaction effects of the multi-dowel connections used in larger structures. We present the results of an experimental test series and probabilistic numerical analysis investigating the development of stiffness in multi-dowel timber flitch plate connections. The influence of the diameter and number of dowels on the stiffness of the connection are investigated, including the influence of off-centring of dowels due to manufacturing tolerances. The test series is used to validate a probabilistic model for the stiffness of such a connection. The model incorporates the nonlinear stiffness and hole opening observed in single-dowel connections to predict the behaviour of the group. The study shows that the random off-centring of dowels in multi-dowel connections reduces the range of displacements over which the connection displays zero stiffness, but that this zone is not eliminated as a result of irreversible hole opening under load.

KEYWORDS: timber connections, slip, stiffness, dowel, glulam, flitch-plate, slotted-in plate

1 INTRODUCTION

Timber connections with steel dowels and flitch (slotted-in) plates provide the high strength and ductility required in large buildings and bridges [1,2]. Single-dowel connections, or multi-dowel connections with a group of perfectly-centred dowels, develop a slip due to opening of the hole in the timber and the oversizing of the hole in the steel plate. This would give the connection zero stiffness under near-zero loads. In reality, the random off-centring of the dowels in a group as a result of tolerances in manufacture and construction can be expected to mitigate this effect. The relationship between the number and off-centeredness of dowels in multi-dowel connections, and the stiffness of those connections, is the object of the experimental and numerical studies presented in this paper.

The deformation of connections is important for the design of timber structures for both static deflection and vibration. The 14-storey Treet building in Norway [3] has more than 200 joints in the trusswork, which have a significant effect on the deflection and vibration of the whole building. Floors with dowelled connections will also depend on those connections for stiffness and vibration properties [4].

The force-displacement behaviour in a single-dowel connection is highly non-linear. Reynolds et al. [5] show substantial irreversible deformation, even under loads approximately 20% of the failure load. They show experimentally a difference between the stiffness under first loading and the subsequent unload-reload and a substantial component of viscoelastic deformation under cyclic loads of approximately 20 minutes' duration.

Dorn et al.'s [6] carefully calibrated finite element model includes elastic-plastic behaviour in steel and timber, and flexible, frictional contact across their interface. This, along with the corresponding experiments shows: the gradual take-up of load; the difference between the initial stiffness and the stiffness under unload and reload; and the residual deformation even after low initial loading.

Reynolds et al. [5,7] find the residual deformation after loading up to 40% of the expected failure load to be approximately 0.2mm for a 12mm dowel in laboratory specimens. Importantly, the condition of the surface of the wood in contact with the dowel appears to have a strong effect on this residual deformation [6], meaning that the manufacturing processes used to make the specimens is important. For this study, the specimens were made by a commercial manufacturer using Computer Numerically Controlled (CNC) drilling, to achieve a quality that is representative of that which would be expected in construction.

Despite the non-linear connection behaviour, it is common to use an equivalent elastic stiffness in design; either by incorporating semi-rigid joints into a model, or

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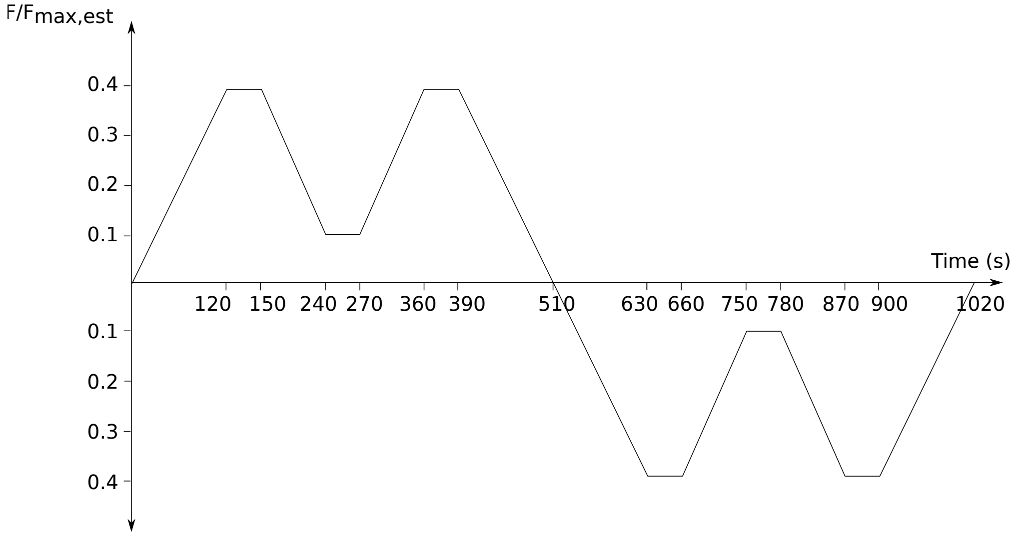

Figure 1: *Loading scheme with load reversals under both tension and compression, applied after the addition of each dowel*

by reducing the stiffness of the members to allow for joint deformation (e.g. [3]). Furthermore, Eurocode 5 design guidance [8] gives an elastic stiffness for a single shear plane of an individual connector, K_{ser}, which is multiplied by the number of connectors and the number of shear planes for each to obtain the stiffness of the connection.

This paper shows that the nonlinear slip in single- and multi-dowel connections may differ greatly from that predicted using K_{ser}; and that the stiffness of a large multi-dowel connection is substantially less than the sum of the stiffnesses of an equal number of single-dowel connections.

2 MATERIALS AND METHODS

2.1 Experimental work

Tests were carried out on specimens of glued-laminated 'whitewood', a term encompassing a group of northern European softwood species, including Norway spruce and silver fir, used interchangeably in engineered wood products. The specimens were manufactured using contemporary CNC manufacturing techniques by Hess Timber Gmbh. Small specimens had groups of five dowels in a line at each end (Figure 2). These dowels were added one by one to each specimen, starting with those nearest to the loaded end of the specimen, with the loading protocol in Figure 1 applied after the addition of each dowel.

This enabled the behaviour of each dowel to be characterised in each direction under initial loading and an unload reload cycle. The loading protocol is based on that from EN 26891 [9], modified to include a load reversal and to test both tension and compression in the specimen.

The maximum estimated load, $F_{max,est}$, was calculated for the full complement of five dowels, including the group effect by using the effective number of dowels from Eurocode 5 [7] and then divided by five to give the estimated load on the first dowel. The load on the connection with two dowels was then double this, and so on. This meant that, assuming load to be shared equally between each dowel in a group, all tests would see the same peak load per dowel.

The irreversible deformation in each dowel after one cycle of load acts to open up the hole in the timber, and this adds to the oversize of the hole in the steel plate to give the total zero-stiffness slip in the connection. This effect is mitigated to some extent by the gradual build-up of interference between the dowels due to their off-centring as a result of manufacturing tolerances, which tends to reduce the zero-stiffness region around zero load. The relationship between these effects was investigated by evaluating the changing stiffness behaviour at near-zero loads as dowels were added.

The test matrix is summarized in Table 1. The 5-dowel test specimen for 12mm dowels is shown in Figure 2. These specimens had a single steel flitch plate at each end and were tested in tension and compression with a load reversal. The large 21-dowel specimens have three flitch plates and three rows of 7 dowels. These specimens were tested in compression only, with any development of slack identified as a residual displacement at zero load.

Tests using 10mm and 12mm dowels investigated the influence of dowel diameter. Since manufacturing tolerances are typically independent of dowel diameter, the oversize of the hole in the steel plate is larger as a proportion of the dowel diameter for the smaller dowels. This leads to a difference in the effect of this oversizing on the resulting slip.

The test with 21 dowels introduced two new influences: multiple rows of dowels, and multiple flitch plates. These compound the effect of construction tolerances, meaning that substantial force was required to install the dowels. The assembly of these specimens required a rotary hammer to be used, rather than the mallet used in the smaller specimens. There would have been a substantial prestressing effect due to the deformation of dowels to accommodate inaccuracies in the hole locations around the steel plates.

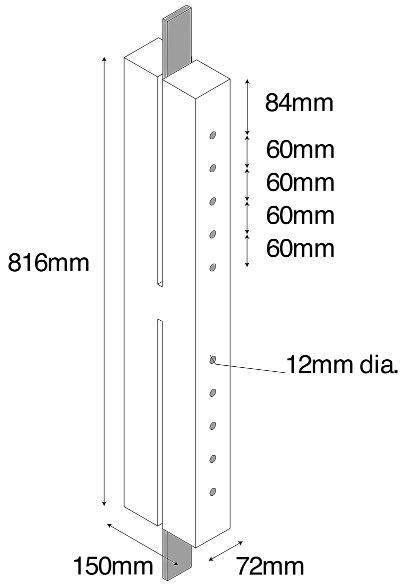

Figure 2: *Specimen dimensions with 12mm steel dowels*

Table 1: *Test matrix*

Specimen size	Dowel diameter	Number of specimens
Small (5 + 5 dowels)	10mm	5
Small (5 + 5 dowels)	12mm	5
Large (21 + 21 dowels)	12mm	2

CNC manufacture by a commercial manufacturer of timber structural components ensured that both the tolerance of manufacture and the nature of the surface of the drilled hole were representative of those which would be expected in real structures.

2.2 NUMERICAL ANALYSIS

The relationship between the increase in the zero-stiffness region due to irreversible deformation in the timber and its reduction due to misalignment of dowels was modelled by a Monte-Carlo simulation. The large 21-dowel connection was modelled, with the dowel positions in the hole represented by a normal distribution, and their force-displacement response represented by two elastic regions (one for compression and one for tension) and a zero-stiffness region. The dashed line in Figure 4shows the response of the 21-dowel connection if all dowels were perfectly aligned in the centre of each hole through the steel plate at zero displacement.

If the dowels are not perfectly centred, as illustrated in Figure 3, then they will not be at the same point in the zero-stiffness region for the same joint displacement and, with sufficient misalignment, there will be no joint displacement for which every dowel is in the zero-stiffness region. This means that, for all displacements, the joint has a non-zero stiffness.

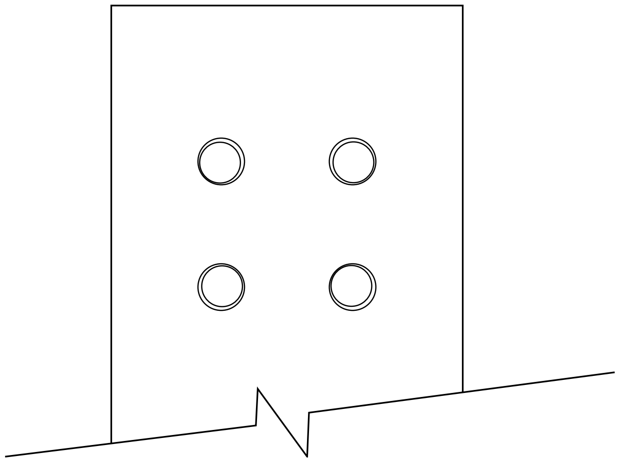

Figure 3: *Illustration of four dowels randomly aligned in a steel flitch plate as a result of tolerances in manufacture*

The position of each dowel in the hole was modelled by a single coordinate. That is, it was assumed that the offset of the dowel in the hole could be modelled by a displacement, and the force in that dowel could be calculated assuming a zero stiffness region and two linear-elastic regions. A Monte-Carlo simulation was carried out using MATLAB, representing the initial coordinate of each dowel by a normal distribution, and generating the coordinates of the 21 dowels for each realization as a set of pseudo-random numbers from that distribution. On this basis, the force in the connection for each realization was calculated for a set of displacements ranging from -2mm to 2mm. The statistical distribution of those forces, or alternatively the stiffness at each point of the force-displacement curve for each realization, was then calculated.

3 RESULTS AND DISCUSSION

3.1 Experimental Work

For each specimen, a force-displacement diagram for the tension and compression loading was recorded for each of the five tests, as the dowels are added one by one. Figure 5 shows that force-displacement diagram for the test on a softwood connection with a single 12 mm dowel.

It can be seen that the zero-stiffness region is approximately double that of the displacement under load up to 0.4 $F_{max,est}$. The initial zero-stiffness region is 2mm, as a result of the oversize of the holes in the steel plate. After the compression and tension loading, the zero-stiffness region increased to approximately 2.2mm, as a result of irreversible deformation of the hole due to embedment of the dowel in the timber. The increase due to irreversible deformation, at 0.1mm on each side, is smaller than the 0.2mm observed by Reynolds et al. [5,7]. This is likely to be due to the difference in the quality of the surface of the drilled hole between the tests; with a flatter hole surface in the commercially-produced specimens used in these tests. The sharpness of the drill bit will reduce with time meaning that pieces drilled at different times in the life of the drill bit may have a different surface quality. This suggests that different levels of irreversible deformation may be expected from dowelled connections in otherwise similar timber elements.

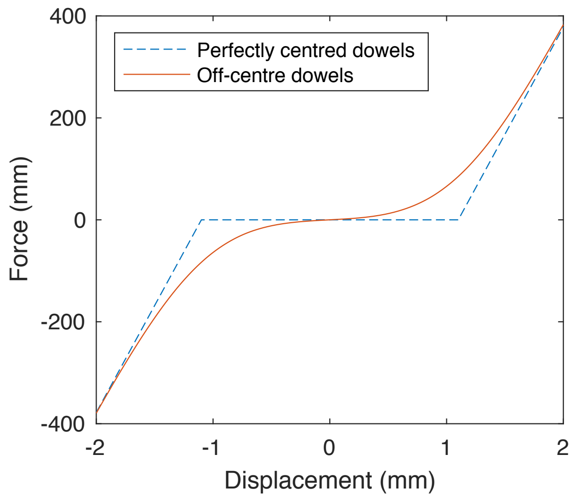

Figure 4: *The modelled force-displacement response of a connection with perfectly centred dowels, and for a single realisation of a 21-dowel connection*

Figure 6 shows the lines fitted to the initial loading and unload-reload curves for the tensile loading region of the force-displacement curve in Figure 5. Once these lines were fitted to both tensile and compressive cycles of load, it was possible to define parameters to characterize the behaviour of the connection once it has seen a tensile and compressive load of 40% of its estimated failure load: the unload-reload stiffness in tension and compression, and the zero-stiffness region. The change in the value of these parameters as more dowels are added allows the group-effect of dowels on stiffness to be assessed for this dowel-group geometry.

The significance of the zero-stiffness region in design calculations would depend on the nature of the structure, its construction process and the nature of the loading on it. If the connection is subject to one-sided loading without reversal, and the designer is interested only in the change in displacement due to live load changes within the range of loads previously imposed on the connection, then the unload-reload stiffness would be more significant. If the connection is subject to load reversal, then the zero-stiffness region is certainly significant, and will greatly affect the global deformation of the structure.

In connections with screws or self-drilling dowels, the slip due to oversize of the hole in the steel plate would not be applicable, but the slip generated by irreversible deformation would be. The magnitude of the effect in screwed connections requires further research, but back-calculation from the difference between stiffness under initial loading and unload-reload in Reynolds et al. [5] shows that there is a substantial effect of irreversible deformation for a screw in embedment, up to approximately 0.45mm for the screws with 12mm outer thread diameter.

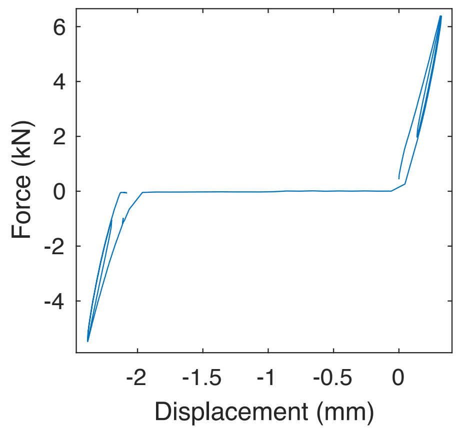

Figure 5: *The measured force-displacement response of a softwood connection with a single 12mm dowel*

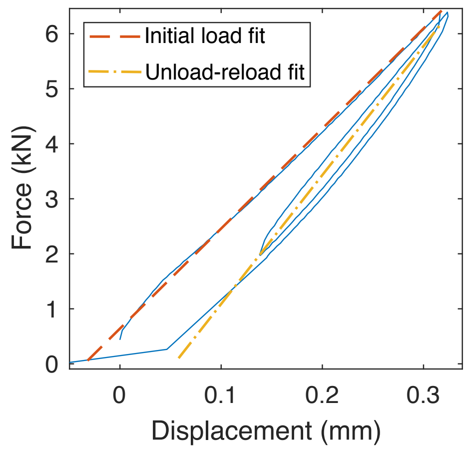

Figure 6: *A detail of the response from Figure 5, showing fits of the initial loading, and the unload-reload portion of the tensile loading curve*

Figure 7 shows the measured gradient of the unload-reload curve for each specimen, as illustrated in Figure 6. The stiffness of the connection increases with the addition of each dowel, but it does not increase in proportion with the number of dowels for either specimen type. Physically, this observation suggests that the strain in the timber which allows the movement of the dowel is not localised in the region of the dowel. In fact, it suggests that the strain field around each dowel is sufficiently large that it interacts with the strain field of the dowels around it, at a distance of 5 times the diameter away.

That interaction substantial. For example, the mean of the unload-reload stiffness of a single-dowel connection with a 12mm dowel is 20.9kN/mm (for two shear planes). For five dowels, the mean is 54.0kN/mm, which could be expressed as an effective number of shear planes of 5.2, approximately half the 10 shear planes present in the connection.

For the 10mm dowels, a single-dowel connection gives a stiffness of 17.2kN/mm, and the five-dowel connection 40.5kN/mm, giving an effective number of shear planes of 4.8.

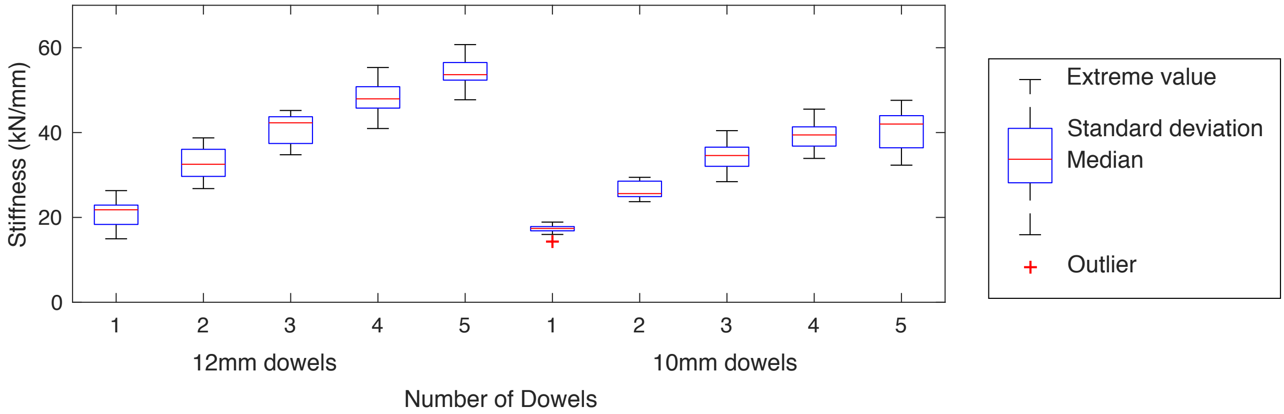

Figure 7: *Unload reload stiffness for connection tests. n=10 for each box (the tension and compression stiffness for each specimen are both included).*

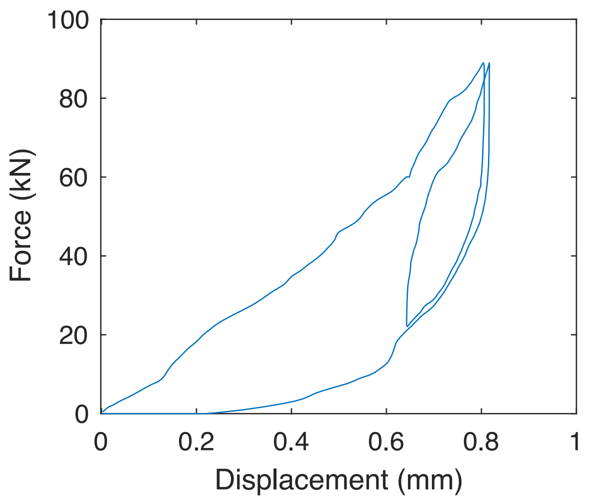

Figure 8: *The measured force-displacement response of 21-dowel connection*

For this timber, with density 378kg/m^3, K_{ser} according to Eurocode 5 is 3.9kN/mm for the 12mm dowels and 3.2kN/mm for the 10mm dowels. These connections have two shear planes, and their deflection is the sum of the deflection of two dowels, so the connection stiffness would be predicted to be equal to K_{ser}. If Eurocode 5 [8] uses the same definition of slip modulus as EN 26891 [9], then the slip modulus K_{ser} would be designed to represent the initial loading curve, neglecting any initial low stiffness at loads lower than 10% of the expected ultimate load. The Eurocode prediction is therefore wildly inaccurate in this case: the initial loading stiffness which has a mean of 15.5kN/mm for the 12mm single-dowel specimen. The only redeeming feature of the Eurocode calculation method is that it is conservative in this case.
An example of the force-displacement curve of the 21-dowel connection is shown in Figure 8. The unload-reload stiffness, at approximately 470kN/m, equates to an equivalent number of shear planes of 45.0. There are 126 shear planes in the connection. Further work is required to reliably define the effective number of dowels in a group for stiffness estimation, and this needs to follow on from a definition of a reliable slip modulus, or, more usefully, a set of slip moduli representing initial loading and unload-reload stiffness.

Taking the intercept of the unload-reload curve, the residual deformation in the 21-dowel connection is at approximately 0.55mm. The connection would therefore be expected to display near-zero stiffness up to this displacement upon reloading. If the behaviour were symmetrical, a total zero-stiffness range of 1.1mm would be created in this connection. This shows that, even in a connection with a large number of dowels and multiple flitch plates, the irreversible deformation in the timber at the hole edge can be sufficient to allow a zero-stiffness region to develop, reflecting the oversize of the holes in the steel plates within.

3.2 Numerical Analysis

The Monte Carlo simulation used 10 000 realisations to estimate the probabilistic distribution of the stiffness of the connection as described in section 2.2. This analysis gives an indication of the reliability of the additional stiffness due to off-centring of the dowels at zero load, and how this might be allowed for in design.
The geometry used in the analysis matched the experimental work, with a 12mm diameter dowel in a 13mm diameter hole in the steel plate. The degree of hole opening was estimated as a 0.1mm initial slip in the timber, based on the five tests on single-dowel connections.
The accuracy of the location of the drilled holes for the dowels was assumed, for the purpose of this simulation, to be such that the standard deviation of the dowel coordinate was 0.5mm. With no experimental data to justify this assumption at this stage, this was simply a plausible estimate to demonstrate the calculation method. Further work will use image analysis of the connections tested to model the distribution of dowel coordinate more accurately.
The results of one realisation of the numerical analysis are shown in Figure 4. For that realisation, shown by the solid line, the random error in dowel location has acted to remove the region of zero stiffness for the connection as a whole. This means that the connection stiffness is non-zero for all displacements of the connection, although it does reduce very close to zero stiffness for near-zero displacements.

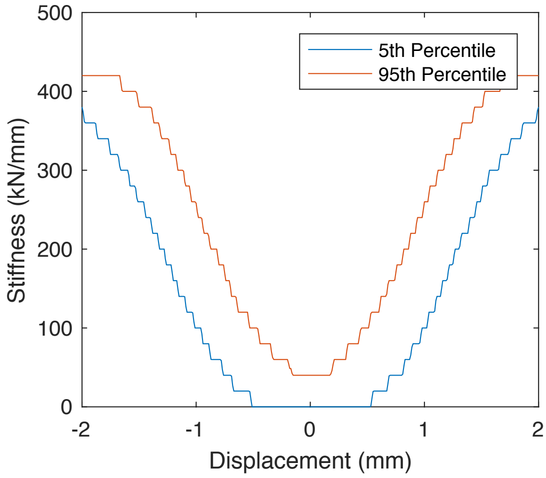

Figure 9: *The force-displacement response of a connection with perfectly centred dowels, and for a single realisation of a 21-dowel connection*

The predicted behaviour of the dowel group with realistically off-centre dowels is far preferable to that of the hypothetical perfectly centred dowels under conditions of load reversal, since the zero-stiffness region around zero load could lead to large displacements in a large structure with many connections at very low loads.
Figure 9 is derived from the statistical distribution of stiffness at each displacement, given by the Monte-Carlo simulation. The two lines show the 5^{th} and 95^{th} percentile stiffness at each displacement level. The steps in these lines indicate the expected displacement at which a dowel moves from its zero-stiffness region to the elastic region, that is, the displacement at which it makes contact with the hole edge. At the 95^{th} percentile, in this case, the stiffness of the connection is always non-zero; there is always a dowel in contact with a hole edge. For the 5^{th} percentile stiffness, there is a zero-stiffness range, however, of approximately 1mm.
This numerical calculation shows that, for a single flitch plate or for dowels drilled straight through multiple flitch plates, even fairly large tolerances of dowel location (a standard deviation of 0.5mm), do not remove the zero-stiffness region. Comparing these results with the 21-dowel three flitch plate connection tested experimentally shows that the zero-stiffness region does develop. The effect modelled here can also explain, at least in part, the lower stiffness of the 21-dowel connection, compared with that which would be expected due to the number of shear planes it has.
It is likely that the lower stiffness of the group of dowels is due both to the interaction of the orthotropic elastic strain fields around them, and the fact that not all dowels are fully engaged due to inaccuracies in their location. The stiffness reduction due to inaccuracies in dowel location would disappear at high loads, although it should be noted that the loads applied here are likely to be higher than the connection would ever experience in-service. The stiffness reduction due to the interaction of strain fields between dowels would not reduce with increased load.

4 CONCLUSIONS

Tests on multi-dowel timber connection systems have measured their slip behaviour. The behaviour is a result of the geometry and material of the connection, and its elastic properties; but also of the manufacturing tolerances. Manufacture by a major European timber manufacturer ensured that those tolerances were realistic and appropriate to contemporary large timber structures.
It has been shown that the Eurocode 5 slip modulus K_{ser} gives a substantial underestimate of the stiffness of these connections.

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